ICM--An Analytical Inversion Charge Model for Accurate Modeling of Thin Gate Oxide MOSFETs

Yuhua Cheng, Kai Chen, Kiyotaka Imai* , and Chenming Hu
Dept. of Electrical Eng. and Computer Science, Univ. of California at Berkeley, Berkeley, CA94720,
* ULSI Device Development Labs. NEC Corp., 1120, Sagamihara, Kanagawa 229, Japan

Abstract--An analytical inversion charge model, ICM, based on surface potential solution and consideration of poly-gate depletion as well as the correction of quantum mechanical effect is presented. It is continuous and accurate from weak inversion to strong inversion, including the moderate inversion region of growing importance for low voltage/power circuits. The model is verified with extensive measured inversion charge data and applied to modeling MOSFET down to 0.13μm channel length.

I. INTRODUCTION

An accurate inversion charge model from weak through moderate inversion to strong inversion (WI, MI and SI) is essential for both device and circuit designs. A charge sheet model (CSM) has been developed [1], but numerical iteration is needed to get the channel charge. Several alternative charge sheet models have been reported [2,3], however, all of them are still numerical in nature. Also, all these numerical models do not consider Fermi-Dirac statistics and the finite thickness of the inversion layer, i.e. quantum mechanical effect (QME). Analytical piece-wise channel charge models have been also developed [4,5]. They can model the charge characteristics accurately in either SI or WI regions, but not in the MI region that is important to low power and analog applications. In this paper, for the first time, we present an analytical charge sheet model based on surface potential approach (SPA) and considerations of QME and poly-gate depletion (PD). It is continuous and accurate. It is also the first time that experimental charge data are used to develop a charge model.

II. PHYSICS AND MODEL

1. Quantization and Polysilicon-gate depletion effects

In current VLSI technologies, MOSFETs continue to be scaled to deep submicron channel length range. For the gate to continue to control the channel efficiently, the oxide thickness needs to be reduced to several nm range and the channel doping concentration needs to be increased to higher than $1x10^{17}cm^{-3}$. This results in very high surface electric field so that the conduction energy band is split into discrete energy level of a 2D electron gas leading to quite different inversion charge density from what the classical theory prediction.

The quantization effect is accounted for by using a correction for the intrinsic carrier density [6,7],

$$n_i^{QM} = n_i^{CL} e^{-\frac{\Delta Eg}{2KT}} \quad (1)$$

$$\Delta E_g = \frac{13}{9}\beta(\frac{\varepsilon_{si}}{4KT})^{1/3} E_{seff}^{\ 2/3} \quad (2)$$

where $\beta = 4.1x10^{-8} ev - cm$ [6,7], n_i is the intrinsic carrier density. E_{seff} is the effective surface electric field, which is, for a NMOS device with n-type polysilicon gate in strong inversion [8],:

$$E_{seff} = \frac{V_{gs} + V_{th}}{6T_{ox}} \quad (3)$$

where T_{ox} is the thickness of gate oxide. V_{th} is the threshold voltage of the device.

The polysilicon-gate depletion effect has been analyzed by several different authors [9,10]. It can be included by subtracting the polysilicon-gate band bending from V_{gs} in the following [9, 11]:

$$V_{gseff} = V_{gs} - V_{poly} \quad (4)$$

$$V_{poly} = V_{gs} - V_{FB} - \phi_s - \frac{q\varepsilon_{si} N_{gate} T_{ox}^2}{\varepsilon_{ox}^2} \left(\sqrt{1 + \frac{2\varepsilon_{ox}^2 (V_{gs} - V_{FB} - \phi_s)}{q\varepsilon_{si} N_{gate} T_{ox}^2}} - 1\right) \quad (5)$$

where V_{gseff} is the effective gate bias considering the polysilicon-gate depletion effect, N_{gate} is the effective doping concentration in polysilicon gate, typically $6 \times 10^{19} cm^{-3}$ [9].

2. Continuous surface potential expression from weak to strong inversion

By solving the Poisson equation with the consideration of quantization effect, an approximate analytical solution for the relationship between the surface potential and gate bias from subthreshold to strong inversion region can be given in the following:

$$\phi_s = \phi_{s0} - V_{bs} + \Delta\phi_{s,sub} + \frac{V_{gs} - V_{th}}{2n} + \frac{(\phi_{ss} - \phi_{s0} + V_{bs})}{2} - \sqrt{[\frac{\phi_{ss} - \phi_{s0} + V_{bs}}{2} - \frac{V_{gs} - V_{th}}{2n} + \Delta\phi_{s,sub}]^2 - \eta\phi_{ss}} \quad (6)$$

$$\phi_{ss} = \phi_{s0} - V_{bs} - \frac{\Delta E_g / q}{2} + \Delta\phi_{ss} + v_t \ln[\frac{(V_{gs} - V_{FB} - \phi_{s0} + V_{bs} - \Delta\phi_{ss})^2}{v_t \gamma^2} - \frac{\phi_{s0} - V_{bs} + \Delta\phi_{ss}}{v_t}] \quad (7)$$

where $\Delta\phi_{s,sub}$ is introduced to account for any difference between the definitions of threshold voltage in subthreshold and strong inversion. n is the subthreshold swing parameter. The dependencies of n and V_{th} on T_{ox}, N_{ch} and body bias are known [12]. ϕ_{ss} is surface potential in strong inversion region (V_{gs} is larger than several Vt above V_{th}). $\Delta\phi_{ss}$ is introduced to account for the difference between the Boltsman and Fermi-Dirac statistics in strong inversion. The quantization effect is accounted for by the correction of surface potential in the third term of (7). η is a parameter extracted from the measured charge data in the moderate inversion region. The polysilicon-gate depletion effect can be accounted for with an effective gate bias given by (4).

Based on the analytical surface potential expression, an inversion charge model (ICM) will be developed below.

3. Inversion Charge Model (ICM)

Separate expressions for channel charge density in strong inversion and subthreshold regions at small Vds were used in most previous MOSFET models. Based on the Poisson equation, a continuous channel inversion charge density Q_{chs0} in both weak and strong inversion regions at the source end can be derived [13]:

$$Q_{chs0} = -C_{ox}\gamma(\sqrt{\phi_s + v_t e^{(\phi_s - \phi_{s0})/v_t}} - \sqrt{\phi_s}) \quad (8)$$

where C_{ox} is the gate oxide capacitance. With the surface potential given by (6), (8) describes the channel charge characteristics from weak inversion through moderate inversion to strong inversion.

To account for the influence of V_{ds}, a unified expression for $Q_{ch(y)}$ with the influence of V_{ds} bias in weak, moderate and strong inversion regimes can be obtained:

$$Q_{ch(y)} = Q_{chs0}(1 - \frac{V_{F(y)}}{V_b}) \quad (9)$$

where $V_b = \frac{Q_{chs0} / C_{ox} + n v_t}{A_{bulk}}$. The parameter $V_{F(y)}$ stands for the quasi-Fermi potential at any given point, y, along the channel with respect to the source. A_{bulk} accounts for the bulk charge effect [12]. Eq. (8) and (9) are the new channel charge model.

III. RESULTS AND DISCUSSION

The measured data are from several different sources with wide process parameters (T_{ox}=45A~70A and $N_{ch}=9 \times 10^{16} cm^{-3} \sim 2 \times 10^{18} cm^{-3}$). We measure the characteristics of gate-channel capacitance versus Vgs of the devices and numerically integrate it to get the channel charge.

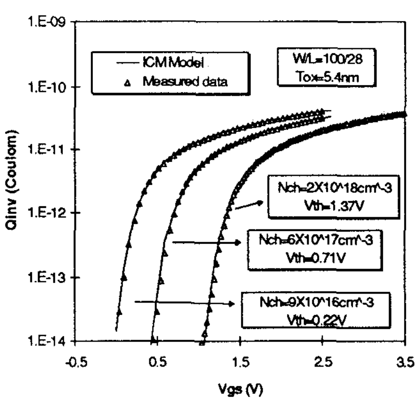

Fig. 1 Modeled and measured channel charges at different channel doping concentrations.

Fig. 1 shows that the model can fit the measured data well in SI, MI and WI at different channel doping concentrations. Figs. 2 and 3 show that the model predicts the measured charge characteristics well at different process and body bias conditions respectively.

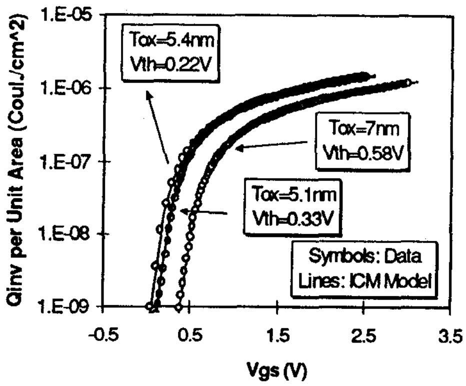

Fig. 2 Modeled and measured channel charges at different gate oxide thicknesses.

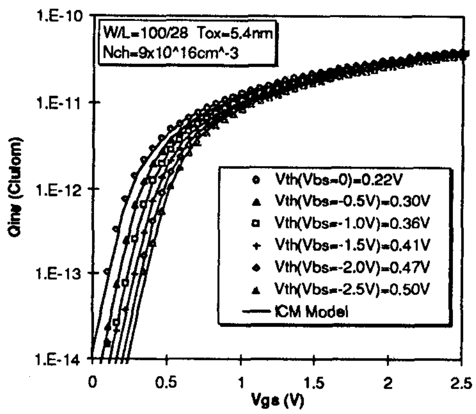

Fig. 3 Modeled and measured channel charges at different body biases.

Fig. 4 compares the model and the numerical CSM [1] for a thick Tox case where the QME can be ignored. The advanced features of ICM makes it very attractive in circuit simulation since the moderate inversion region is becoming more important for low voltage/power circuit application, and no other analytical charge models describing the charge characteristics based on continuous surface potential in the MI region have been reported.

Another advantage of ICM is that it can incorporate short channel effects easily. A unified I-V equation can be derived based on ICM. In Figs 5 and 6, we show the comparison results of the modeled and measured characteristics of Id-Vg and gm/Id, which is a sensitive test for the

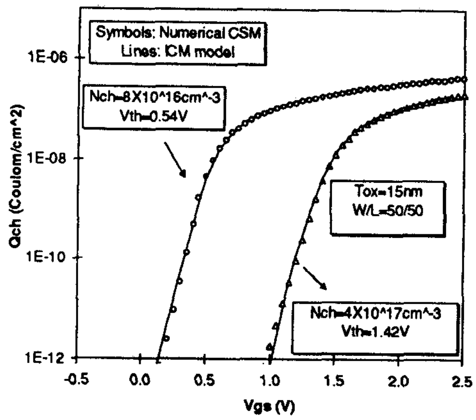

Fig.4 For thicker Tox, i.e. inversion layer thickness is negligible, ICM agrees with the numerical CSM.

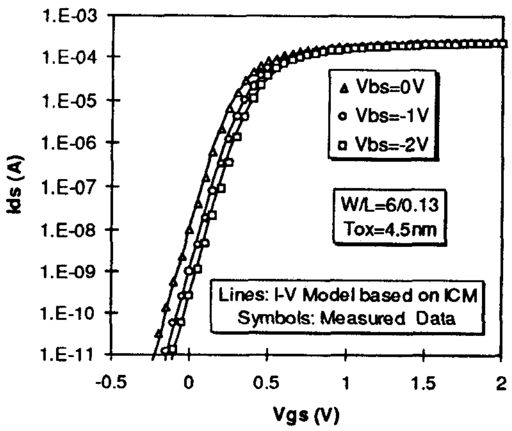

Fig. 5 Measured and Modeled I-V characteristics based on ICM.

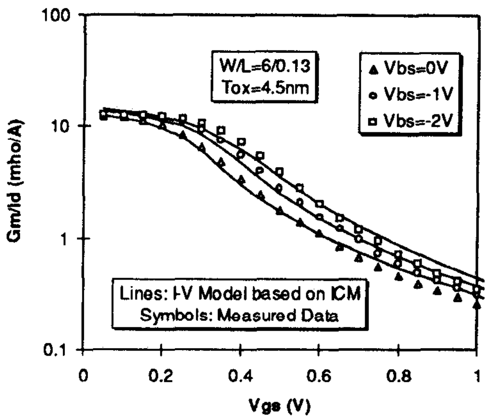

Fig.6 Measured and modeled Gm/Id curves.

accuracy of a charge model. By accounting for the short channel effects in the charge model, the

I-V model can predict the current characteristics very accurately for the devices with channel length down to 0.13μm, as shown in Fig. 5 and Fig 6.

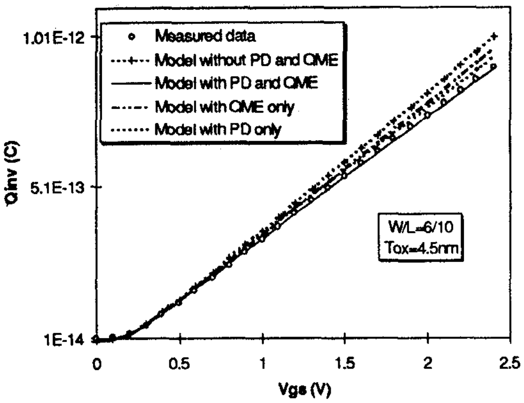

Fig. 7 Comparisons of the measured charge and ICM (1) without PD and QME, (2) with PD only, (3) with QME only, and (4) with PD and QME.

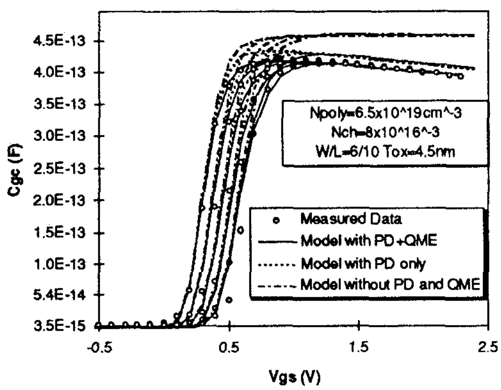

Fig. 8 Comparisons of the measured CV and ICM capacitance (1) without PD and QME, (2) with PD only, and (3) with PD and QME.

With the consideration of PD and QME, the model can accurately describe the charge and capacitance characteristics of the devices of very thin oxide thickness, which can be shown in Figs. 7 and 8. The model simulation results, without PD and QME, with PD only or with QME only are also given for comparison. The results show that the PD and QME must be accounted for in the devices with very thin gate oxide thicknesses.

IV SUMMARY

An analytical inversion charge model (ICM) including polysilicon-gate depletion and channel quantization effects is developed based on the surface potential approach. It is with a fully closed form and accurate and continuous from weak inversion to strong inversion. The model has been verified with the measured data of inversion charge, and can fit the data well from weak inversion to strong inversion including the moderate inversion region for several processes and bias conditions.

An *I-V* model is also derived from ICM. *I-V* and G_m/I_d plots demonstrate excellent accuracy and continuity in the moderate inversion region. With the consideration of polysilicon-gate depletion and quantization effects, ICM can accurately describe the charge and capacitance characteristics of the devices of very thin oxide thickness.

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